NIST Metrology Research --
Laying the Foundations for Continued Semiconductor Technology Advances

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Good afternoon, my name is Daryl Hatano and I am Vice President for Public Policy for the Semiconductor Industry Association. This morning I would like to

- describe the U.S. semiconductor industry and the technical challenges it faces; and
- highlight the importance of NIST metrology research to insure that the industry can continue to drive American economic growth.

The Exponential Increase in Transistors Drives Economic Growth

The semiconductor industry employs 226,000 people across the U.S. and contributes $41 billion to U.S. GDP. However the industry's real impact is due to its role in creating the enabling technology behind computers, telecommunications, consumer electronics, and the internet. The industry's ability to continually manufacture chips that are better, faster, and cheaper is driving increased productivity and creating more jobs throughout the economy.

Propelling the ever expanding role of semiconductor's in our economy is the ever shrinking transistor. The transistor is the basic building block within the semiconductor chip. For over three decades the industry has followed Moore's Law, which states that the number of transistors on a chip will double every eighteen months. A decade ago, we were able to integrate thousands of transistors on each silicon chip. Today we can integrate millions of transistors on each chip.

Cramming millions of transistors on each chip makes semiconductors the most complex structures manufactured today. To get an idea of how precisely the features on each chip are placed, image drawing a map of New York City that is so accurate that you can identify features on each street that are only 1.5 inches long – and this map is only the size of a postage stamp.

By integrating millions of transistors on each chip, and by producing those chips by the millions, we estimate that today about 30 billion transistors are produced worldwide every second.

The International Roadmap for Semiconductors sets a Timetable for Technology Advances

To continue to pack more transistors on each chip, over 800 hundred of chip experts around the world contribute to “The International Technology Roadmap for Semiconductors” (ITRS). The North American participation of the ITRS is under the auspices of the SIA, and NIST participates in the ITRS metrology workshops – in fact one of the first meetings of what is now the ITRS was held at NIST’s Boulder, Colorado facility.

The ITRS identifies the milestones that will need to be reached in all aspects of semiconductor manufacturing for technology trends such as Moore’s law to continue. For example, microprocessor transistor gate lengths – a critical dimension that affects the processor’s speed -- must decrease from 37 nanometers in 2004 to 18 nanometers in 2010 and 7 nanometers in 2018 if microprocessors are to continue to increase in speed. (Note: a nanometer is one-billionth of a meter. A human hair is 100,000 nanometers in width, and a red blood cell is 5,000 nanometers in width.) If these and other milestones identified in the ITRS are reached, microprocessors would be three times faster.

The ITRS also finds that we are beginning to reach the fundamental limits of the materials used in the planar CMOS process, the process that has been the basis for the semiconductor industry for the past 30 years. By introducing new materials into the basic CMOS structure and devising new CMOS structures, further improvements in the CMOS process can continue for the next ten to fifteen years, at which time it becomes evident that most of the known technological capabilities of the CMOS device structure will approach or have reached their limits. In order to continue to drive information technology advances, it becomes necessary to investigate new devices that may provide a more cost-effective alternative to planar CMOS in this timeframe.

The ITRS lists the technical barriers at each stage of production that must be overcome if we are to continue to enjoy the benefits of chip technology advances. One important set of challenges is in the area of metrology. New metrology tools and techniques are needed to accurately perform critical measurements as new materials, processes, and device structures are introduced. These measurements are not only the obvious measurement of linear dimensions (nanometers) but also includes measurements such as a material’s electrical characteristics, the aspect ratio of nanoscale trenches etched into chips, the thickness of oxide layers that are only a few atoms thick, and the size of pores inside of thin layers of materials.

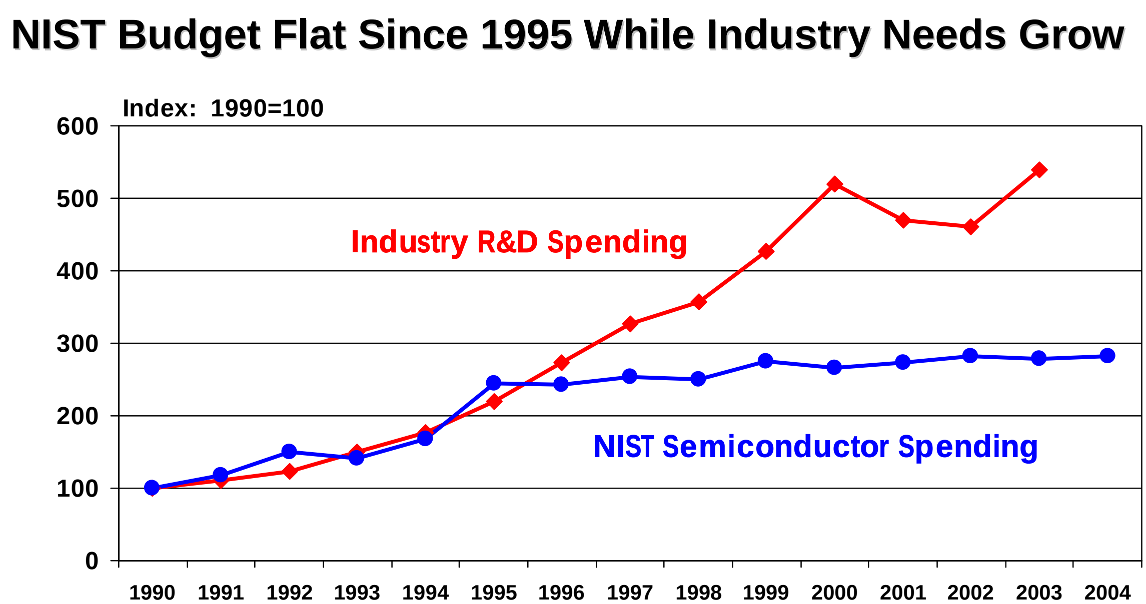
The ITRS metrology chapter lists 112 measurements and controls and the required accuracy levels that must be met at specific points in time if semiconductor technology is continue to advance at current rates from now until 2018. The ITRS also identifies areas where further research is needed. For example, for 59 of these 112 measurements there are currently no known manufacturing solutions for the levels of accuracy that will be required on the factory floor in 2009 – a mere five years away.

NIST’s Ability To Meet The Challenges Has Not Kept Pace With Advance Of Technology

NIST is the leader in semiconductor metrology research, and has made a number of contributions in recent years. Recently a NIST paper on the measurement of the roughness of the edges of the lines etched on semiconductor chips, a major topic of concern identified in the ITRS, won a best paper award from the International Society for Optical Engineering. NIST was also the first to note that light traveling through Calcium Fluoride (CaF) lenses at different speeds created distorted images, a problem for semiconductor makers as shorter wavelengths of light were used to expose patterns on semiconductor chips.

While these contributions are notable and underscore NIST's potential, NIST's level of effort has not kept pace with needs brought on by technology advances. Three indications of the shortfall are provided by comparisons with industry R&D spending, detailed analysis of ITRS needs, and an evaluation of NIST tools.

NIST spending on semiconductor research has only increased 15 percent since 1995. As an indication of the growing technical challenge as circuits continue to shrink, the semiconductor industry's total investment in R&D increased 145 percent during that period. See Figure 1.



NIST S/C Spending ($M)	$6.4	$7.5	$9.5	$9.0	$10.6	$15.5	$15.5	$16.2	$15.9	$17.5	$16.9	$17.5	$18.1	$17.8	$18.0
R&D Spending ($B)	$2.6	$2.9	$3.2	$3.9	$4.6	$5.7	$7.1	$8.5	$9.3	$11.1	$13.5	$12.2	$12.0	$14.0	

Note: Industry data for calendar year, NIST Fiscal year starting in October of prior year. NIST semiconductor spending refers to the Office of Microelectronics Programs and the Semiconductor Electronics Division. In addition, NIST estimated in 2000 that there was an estimated $7M on broader research of value to semiconductors in other NIST divisions.

Source: SIA Databook, NIST

Figure 1

Another indication that NIST spending is well below what is required comes from a detailed analysis of the ITRS by the Semiconductor Research Corporation that estimated that 480 person-years should be devoted each year to meet the metrology challenges; at a cost of over $100 million dollars. The total worldwide research currently aimed at these challenges is only a fraction of this amount. A third indication that NIST spending has fallen short of what is required is to compare the current lithography equipment at the NIST lab with current market requirements. Lithography, the ability to use exposures of light through masks to etch microscopic patterns on silicon, is a key step in semiconductor manufacturing. NIST's lithography equipment can etch patterns with a feature size of 1 micron, while the current industry standard is approaching 0.13 microns (or 130 nanometers), and sub-100-nanometers devices are coming soon.

SIA Recommendations to Congress for NIST and Other Research Agencies

The SIA supports the Administration proposal for increased spending at the NIST laboratories, and specifically **$25.5 million to equip the Advanced Measurement Laboratory, $15.6 million for advances in manufacturing (including $4 million for electronics and semiconductor nano-metrology).** These increases represent a good first step toward achieving the funding level at NIST that was envisioned when the NIST Office of Microelectronics was established in 1994. SIA would encourage NIST to insure that a portion of this increase is devoted to funding for university research in metrology.

The budget increases at NIST aimed at metrology issues should be done in concert with increased appropriations for other programs in semiconductor research at universities. SIA supports significant increases in the NSF budget, and in particular funds focused on nanoelectronics research as authorized in the Boehlert-Honda Act.[1] The House Appropriations report for NSF noted the importance of semiconductor advances to continued productivity growth in our economy and encouraged the NSF to increase research aimed at the challenges outlined in the ITRS.[2] The House Science committee might consider similar language in its report to support increased alignment of NIST research and the priorities identified by the ITRS. SIA also urges Congress to appropriate $20 million for the Defense Department's Government-Industry Cosponsorship of University Research program.[3] This program funds the Semiconductor Focus Center Research Program at 30 universities across the country.[4]

Increased Spending on Chip Research Benefits the Federal Budget

While the SIA recognizes that this is a difficult budget year for the Congress, it is instructive to view the research costs required to meet the ITRS timetables from the perspective of the costs to future Federal budgets if the timetables are not met. On both the revenue and spending side, the government receives a multifold return on its investment.

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[1] 21st Century Nanotechnology Research and Development Act; Public Law No: 108-153

[2] "From within the Engineering Directorate, the Committee is concerned that researchers are reaching the physical limits of current complementary metal oxide semiconductor (CMOS) process technology and that this will have significant implications for continued productivity growth in the information economy. The Committee encourages NSF to examine the challenges and timelines outlined in the most recent International Technology Roadmap for Semiconductors and, where feasible, increase research support in this area accordingly." House Rpt.107-740 - Departments Of Veterans Affairs And Housing And Urban Development, And Independent Agencies Appropriations Bill, 2003.

[3] The Government-Industry Cosponsorship of University Research (GICUR), program element number 0601111D8Z, is funded through the Office of the Secretary of Defense.

[4] For further information on the Focus Center Research Program, see http://fcrp.src.org

The CBO budget deficit models assume that even a 0.1 percent/year increase in GDP growth results in a $236B smaller Federal deficit over 2005-2014, largely due to increased tax revenues collected. In its projection of a $1.8 trillion deficit for FY2005-2014, the Congressional Budget Office assumes the 0.7 percentage point surge in productivity that was experienced from 2001 to 2003 does not continue. The CBO does recognize, however, that

> "…. Computers and other information-related technologies are fundamentally transforming the way the economy works, much as the electric dynamo and the internal combustion engine did in previous eras. If that hypothesis is valid, productivity growth might remain faster than its historic average during a transition period that could last several decades."[5]

Economists have noted the acceleration of semiconductor product cycles from 3 years to 2 years as a key driver of the surge in productivity. Because of the ubiquity of semiconductors in our economy, the acceleration or deceleration of semiconductor technology advances has a pronounced impact on productivity growth and GDP. The Federal dollars needed at NIST, NSF, DOE, and DOD to support the basic research at universities and national labs related to semiconductors and nanoelectronics are small relative to the economic growth and added tax revenues that would ultimately accrue to the government.

It addition to the benefits from economic growth, and added taxes, that the government receives from semiconductor technology advances, it is also possible to quantify the benefits that government (Federal, state, and local) receives as a consumer of semiconductors. The Bureau of Economic Analysis at the Department of Commerce has data indicating that the government sector of the economy purchased $8.9 billion of computers in 2003, but that they would have had to spend $106 billion for that same amount of computing power if they had to pay 1994 prices. The cumulative benefit from technology improvements and resulting price declines from 1994 to 2003 is $363 billion of "free" computing.

Summary

For the past five decades, semiconductors have become ever faster, better, and cheaper, and today are a major driver of growth in economic productivity. As we approach the physical limits of the chip making technology that we have used for the past 30 years, technology advances are becoming ever more difficult. Metrology challenges are among the most important as they cut across all of the manufacturing stages in chip production. Basic research funded by the Federal government is needed if we are to continue to advance our current technology as well as find a replacement technology before the aforementioned physical limits are reached. Congress must increase the NIST laboratory budget if the country is to continue to enjoy the benefits of every increasing semiconductor capabilities at ever decreasing costs.

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[5] Source: "The Budget and Economic Outlook: Fiscal Years 2005-2014" Congressional Budget Office, January 2005.